

ICE DETECTION APPARATUS AND METHOD

The present invention relates to apparatus and methods for detecting and monitoring ice accretion, and in particular, but not exclusively, on aircraft surfaces.

5 Ice accretion on flying surfaces affects the aerodynamic performance and handling qualities of an aircraft, and may require different pilot corrective action, dependent upon the surface that ice is accreting onto.
10 Current methodology for ice detection usually relies on an indirect method, normally based on ambient air temperature, and liquid water content. When a pre-set threshold level is reached, the ice protection system is activated, whether or not ice is accreting on critical surfaces.
This method is not cost effective or efficient for an ice protection system.

Known ice sensor arrangements are capable of detecting the presence, and with some the thickness, of ice, however they all offer challenges for
15 integration into a distributive network. Furthermore the known ice sensor arrangements do not give an indication of the type (or roughness) of ice accretion, which has a marked influence on the aerodynamic performance of an aircraft.

20 The present invention seeks to provide an alternative ice detection apparatus and method.

According to a first aspect of the invention there is provided apparatus for detecting ice accretion comprising an electromagnetic radiation emitter and an array of sensors, the emitter being located intermediate of the array of sensors and at least some of the sensors being located at
25 different distances from the emitter.

Most preferably the sensors are substantially symmetrical about the emitter.

Preferably the sensor array comprises first and second sets of sensors which are arranged in generally opposing respective paths away from the
5 emitter.

Preferably the sets of sensors are arranged in respective straight lines. Alternatively the sets of sensors may be arranged to follow respective curvilinear paths which may be (mirror) symmetrical about the emitter.

The apparatus may comprise third and fourth sets of sensors which are
10 arranged to follow (generally opposing) respective paths generally away from the emitter. Preferably the first and second sets of sensors, and the third and fourth sets of sensors together form a substantially cruciform arrangement of sensors about the emitter.

The array of sensors may be asymmetrical about the emitter.

15 The emitter need not necessarily be located at the geometrical centre of the array of sensors.

According to a second aspect of the invention there is provided a method of monitoring ice accretion comprising emitting an electromagnetic radiation signal from an emitter, detecting diffused radiation which
20 comprises radiation scattered and/or reflected by a layer of accreted ice, detection of the diffused radiation being effected by an array of sensors, at least some of the sensors being at different distances from the emitter, and the method further comprising comparing detected intensity of the diffused radiation at a particular distance from the emitter a respective
25 predetermined value so as to determine the type of accreted ice.

Preferably the method comprises determining the thickness of ice which has accreted on an aircraft surface.

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- 5 The method desirably comprises comparing the detected spatial distribution of intensity of the diffused radiation to stored data representative of the spatial distribution of intensity of the diffused radiation in the ice for different ice types.

According to a third aspect of the invention there is provided data processing equipment for ice detection apparatus comprising comparator means, the comparator means, in use, receiving signals representative of the intensity of diffused radiation which comprises radiation scattered and/or reflected by a layer of accreted ice, which diffused radiation is detected by an array of sensors, at least some of the sensors being located at different distances from an electromagnetic radiation emitter, the comparator means being configured to compare detected intensity of the diffused radiation to a predetermined value and determine whether said value detected intensity is above the predetermined value so as to enable the data processing equipment to determine the type of accreted ice.

Various embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a schematic representation of an ice detection apparatus for an aircraft;

- Figure 2** is a schematic representation of part of the ice detection apparatus of Figure 1 which shows reflected and scattered light from an accreted layer of ice;
- 5 **Figure 3** is a cross-sectional view of aircraft surface which is provided with flush mounted fibre optic cables;
- Figure 4** is a schematic plan view of an array of sensors disposed diametrically about a central emitter;
- Figure 5** is a schematic plan view of a second array of sensors which are arranged in a cruciform about a central emitter;
- 10 **Figure 6** shows a schematic plan view of a third array of sensors which are arranged at various angles to the skin of an aircraft;
- Figure 7** shows curves of intensity against sensor position for different ice types;
- 15 **Figure 8** shows curves of intensity against ice thickness for different ice types;
- Figure 9** is a schematic perspective view of a diode emitter and sensor head;
- Figure 10** is a plan view of the diode emitter and sensor head shown in Figure 9;
- 20 **Figure 11** is a schematic perspective view of a rotorcraft blade and associated equipment, the blade being provided with multiple emitter and sensor arrangements,

Figure 12 is a schematic representation of the electronic components of the data acquisition unit of the ice detection apparatus of Figure 1,

5 **Figure 13** is a truth table showing how the possible various outputs of the comparators correspond to different ice types, and

Figure 14 is an alternative emitter/sensor configuration.

With reference to Figure 1 there is shown an apparatus 1 for monitoring ice accretion on an aerofoil 9, which apparatus comprises a light emitter 10, and sensors 3, 4, 5, 6, 7 and 8.

10 As is seen from Figure 3, the ice monitoring region 2 of the aerofoil 9 comprises the emitter 10 which comprises central fibre optic cable, and six sensors 3, 4, 5, 6, 7 and 8 which are provided by single mode fibre optic cables disposed diametrically about the emitter 10. The emitter 10 and the sensors 3, 4, 5, 6, 7 and 8 are accommodated in respective
15 holes 16 which have been drilled into the aerofoil 9. The emitter and sensors are flush mounted (ie air conformal) with the outer surface 17 of the aerofoil 9. The distance between the longitudinal axes of adjacent sensors, and between the longitudinal axis of the emitter 10 and the longitudinal axes of the sensors 5 and 6 is 1 mm. The emitter 10 is
20 connected to a radiation source 10'.

The apparatus 1 further comprises ambient light filters 11 which receive optical signals from the sensors 3, 4, 5, 6, 7 and 8. The signals from the filters are then received by a diode array 12 which converts the optical signals into electrical signals. The output of the diode array 12 is then
25 fed into a data acquisition unit 13 and the output from the data acquisition unit 13 to a control unit 14.

The data acquisition unit 13 is configured to determine ice thickness and type, and to better understand the structure of this unit some explanation of various types of ice is now given.

Glaze/Clear ice, as its name suggests, is optically clear and very little
5 light is scattered.

Rime ice is optically opaque and air is trapped in volume of the ice resulting in micro-scattering centres. Accordingly rime ice scatters light much further from a source than clear ice.

Mixed phase ice, as its name suggests if anything in between, to the
10 amount of scattering of light is dependent upon the content of glaze and rime ice.

In the case of rime ice growth, and for small thickness of ice, the dominant contributions to the optical signal detected by the fibres are due to light scattered from air trapped in the ice layer, giving rise to a
15 rapidly increasing signal with ice thickness. However, as the ice thickness increases, and the ice-air interface recedes away from the fibres the optical contribution of light scattered from the ice-air interface also decreases and scattering from the main ice volume becomes more significant. This results in a slower rate of increase in intensity with ice
20 thickness. In rime ice all fibres, on both sides of the light source, exhibit similar behaviour but at reduced signal strength (with increasing distance away from the light source) due to the regular optical diffusion.

In the case of glazed or clear ice, which is transparent and has a very irregular structure due to the aerodynamics of the aerofoil, with pointed
25 ice-air interfaces and micro-cracks, light is randomly reflected or scattered therefrom. Consequently for small ice thickness, the dominant

contribution to the optical signal detected by the fibres, is due to the random reflections and scattering from the volume and surface irregularities. However as the ice thickness increases the surface irregularities can potentially contribute to the optical signal, as the ice is
5 mostly transparent, but these contributions are random, and scattering from the ice volume micro-cracks dominate. The characteristic optical signature, detected by the fibre optics during the ice growth of this type of ice, exhibits a general increase of the optical signal with ice thickness with large fluctuations related to the random scattering at the ice air
10 interfaces.

Figure 7 shows three curves 90a, 90b, 90c of detected intensity against sensor position. The curve 90a represents the 'spatial signature' of glazed or clear ice, the curve 90b represents the 'spatial signature' of mixed phase ice, and the curve 90c represents the 'spatial signature' of
15 rime ice.

Referring to Figure 8 there is shown a family of curves 91a, 91b, 91c and 91d of the average detected intensity (measured at a particular distance from the emitter) against ice thickness. The curve 91d is representative of rime ice, and the curve 91a is representative of glazed or clear ice. The curves 91b and 91c are representative of mixed phase ice types, with the curve 91c representing ice having a greater rime ice
20 content than the ice which is represented by curve 91b.

The data acquisition unit 13 is shown in more detail in Figure 12. The unit 13 comprises three comparators COMP1, COMP2 and COMP3, a
25 logic array 100, an analogue to digital converter 95, a memory map 96 and a digital to analogue converter 97.

One input of each of the comparators COMP1, COMP2 and COMP3 is connected to the outputs of operational amplifiers OPAMP1, OPAMP2 and OPAMP3 respectively. The operational amplifiers OPAMP1, OPAMP2 and OPAMP3 are provided with feedback resistors R1, R2 and 5 R3 respectively, and input resistors R10 and R11, R12 and R13, and R14 and R15 respectively. The input resistors are connected to the photodiodes PD1, PD2, PD4, PD5 and PD6, which receive signals from the respective optical fibres of each of the sensors 5, 6, 4, 7, 3 and 8 respectively. Operational amplifier OPAMP1 receives input from PD1 10 and PD2, operational amplifier OPAMP2 receives input from PD3 and PD4, and operational amplifier OPAMP3 receives input from PD5 and PD6.

Outputs of the comparators COMP1, COMP2 and COMP3 are connected to a logic array 100 which comprises two exclusive-OR gates 101 and 15 102 and two AND gates 103 and 104.

The eight bit analogue to digital converter 95 receives an input from OPAMP1 and the output of the converter 95 is connected to the memory map 96, as is the output of the logic array 100. The memory map 96 has stored therein look-up tables representative of detected intensity values 20 and corresponding ice thickness values for various ice types as detected by sensors 5 and 6 (ie those sensors closest to the emitter 10). These values in the look-up tables are based on the various curves shown in Figure 8.

The output of the memory map 96 is input into a digital to analogue 25 converter 97 which produces an output 98.

In use the apparatus 1 operates as follows. Radiation in the wavelength range 500 nm to 1300 nm is generated by light source 11 and emitted from the distal end of the emitter 10 which is arranged to be substantially flush with the outer surface 17 of the aerofoil 9. The light issuing from
5 the emitter 10 is directed generally outwardly of the outer surface 17. As best seen in Figure 2 light enters a layer 15 of accreted ice on the aerofoil 9, some of the light is reflected back towards the aerofoil at the boundary 20 between the accreted ice and the air 21. Some of the emitted light is scattered by the ice layer 15 back towards the aerofoil 9.
10 That diffused radiation comprising the reflected and scattered light is received by the flush-mounted distal ends of the sensors 3, 4, 5, 6, 7 and 8.

The signals from the photodiodes PD1, PD2, PD3, PD4, PD5 and PD6 are amplified by operational amplifiers OPAMP1, OPAMP2 and
15 OPAMP3, the outputs of which are input to the respective comparators. As can be seen from Figure 12, one input of each comparator COMP1, COMP2 and COMP3 is held at a threshold voltage. In particular one input of COMP1 is held at a threshold voltage determined by R4 and R5, one input of COMP2 is held at a threshold voltage by R6 and R7, and
20 one input of COMP3 is held at a voltage determined by R8 and R9. The respective threshold voltages are determined in accordance with the data from Figure 7. If an (amplified) signal from connected photodiodes exceeds the threshold voltage then the comparator outputs a '1', otherwise the comparator issues an '0'. The outputs of the comparators
25 are input into the logic array 100, the logic array being configured to implement the truth table shown in Figure 13. Thus a two-bit output 99 results which is indicative of the type of the accreted ice layer. In the truth table:

00	-	No ice
01	-	glaze/clear ice
10	-	mixed phase ice
11	-	rime ice

- 5 As is evident if comparators COMP3 and/or COMP2 output a '1' this indicates wider scattering.

The thickness of the accreted ice layer 15 is determined in the following way. Returning to Figure 12, it can be seen that the output of OPAMP1 is fed to the analogue to digital converter 95. This signal provides a
10 non-linear measurement of ice thickness. Since ice type has been determined, and is given by output 99, the appropriate look-up table stored in memory map 96 can be selected. It is then a straightforward operation to locate in the appropriate look-up table the detected intensity value input by the converter 95 and read the corresponding ice thickness
15 value. The converter 97 then converts that value into an analogue signal 98.

Signals from the data acquisition unit 13 are then fed to the control unit 14. The control unit uses the signals from the data acquisition unit 13 to apply power to the aircraft ice protection system (IPS).

- 20 The way the IPS is configured will be dependent upon the application of the sensors. With a single sensor system, the control unit will apply an algorithm to determine the required de-icing sequence given the current conditions. A multi-sensor system on the other hand has the capability to apply the de-icing sequence dependent upon the specific ice build up at
25 that point on the airframe/airfoil.

A further simplified use of the apparatus 1 would be to provide an 'ice/no ice' indication. This would be useful to the pilots of smaller general aviation aircraft without ice protection systems fitted, to allow for easier identification of wing or tail stall due to ice accretion.

- 5 With reference to Figure 11 there is shown a helicopter blade 25 which is provided emitter/sensor configurations 26, 27, 28, 29 and 30 which are arranged to monitor ice accretion along the length of leading edge 31 of the blade 25.

Each emitter/sensor configuration comprises a central emitter
10 (unreferenced) in the form of a fibre optic cable which interposes two diametrically opposed sensors (unreferenced) also provided by fibre optic cables. Each emitter/sensor configuration is arranged to monitor a respective zone of the blade 25. The fibre optic cables, which would typically be embedded in the blade, are arranged to lead to the inboard
15 end of the blade 25 to pre-amp and link electronics 32. A link 33 comprises an optical slip ring which allows the sensed data to pass from the rotating blade 25 to the frame of the aircraft. The aircraft then houses an optic module 34 and computer and control electronics 35.

This 'distributive architecture' opens up the possibility for multiple ice
20 protection technologies to be used on the same aircraft in different areas.

There are numerous other ways in which the invention could be embodied. In one preferred embodiment the emitter and sensors are provided as an integral unit in the form of an emitter/sensor head which may be installed into an aircraft by making a suitably sized recess
25 therein. Signals would be sent back to remotely located data processing equipment.

In yet a further embodiment shown schematically in Figures 9 and 10, an emitter/sensor head may comprise an array of photodiodes (which serve as sensors) 41 to 50 and a central light emitting diode 40.

With reference to Figure 5 there is shown an alternative emitter/sensor arrangement 70 wherein fibre optic cables 73 are arranged in two sets of sensors, one on each side of a light emitting fibre optic cable 72, and fibre optical cables 71 are arranged in two similar sets about cable 72, but at substantially 90° relative thereto. It will be appreciated that the centre spacings between adjacent cables 71 and adjacent cables 73 need not necessarily be the same, so

$x_1 = or \neq x_2 = or \neq x_n$, and

$y_1 = or \neq y_2 = or \neq y_n$

This cruciform arrangement not only increases the detection area, but also provides a degree of redundancy in the arrangement.

Figure 6 illustrates that emitter and/or sensor cables 80 and 81 need not necessarily extend substantially perpendicular to the outer surface of the aircraft, and moreover, $\theta_1 = or \neq \theta_n or \neq \emptyset$.

The spacing between the centres of adjacent optical fibres could typically be in the range 40 μm to 5 mm, for example.

Figure 14 shows an alternative emitter/sensor configuration which comprises an emitter 110 and a plurality of sensors 111. The sensors 111 are arranged in a substantially spiral path (shown by broken line 112) around the intermediately located emitter 110, and accordingly the

sensors are located at progressively greater distances from the emitter 110.

- In an alternative embodiment the output of the comparator COMP3 is used as an ice type indication and is connected directly to the control unit
- 5 14. As is evident if the output of the comparator COMP3 issues a '1' rime ice is present. If, however, a '0' is issued one of either no ice, clear/glazed ice or mixed phase ice is present. Although such an embodiment is less informative than the embodiment of Figure 12, it may nevertheless find utility in particular applications.
- 10 10 In yet a further embodiment modified comparator means is configured to issue a '1' if the respective input signals representative of detected intensities of diffused radiation are within respective particular predetermined ranges of values, otherwise a '0' is issued.